The Effect of Core Configuration on Thermal Barrier Thermal Performance

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  - Construction of CTB’s
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    - Effect of core density on flow/leakage → permeability
    - Thermal conductivity effect
  - Modeling Studies
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    - Effect of various parameters on temperature
- Summary

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An Integral Part of the TPS

Compliant Thermal Barriers (CTB's)

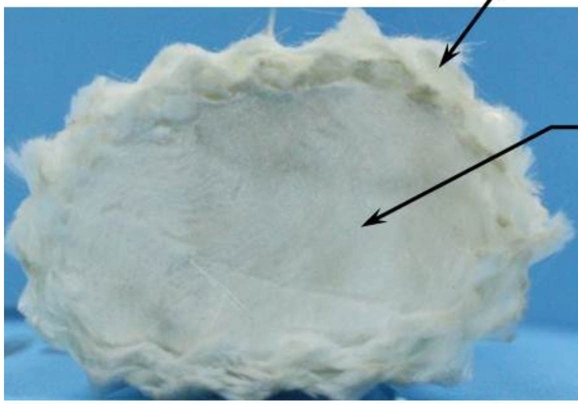
- Often referred to as "thermal seals" or "seals"
- One "class" of thermal barriers
- High-temp. ceramic-based fibrous materials
- Installed in TPS interface gaps
- Roles
  - Thermal – limit inboard temperatures
  - Structural – accommodate deflections

Vehicle Penetrations

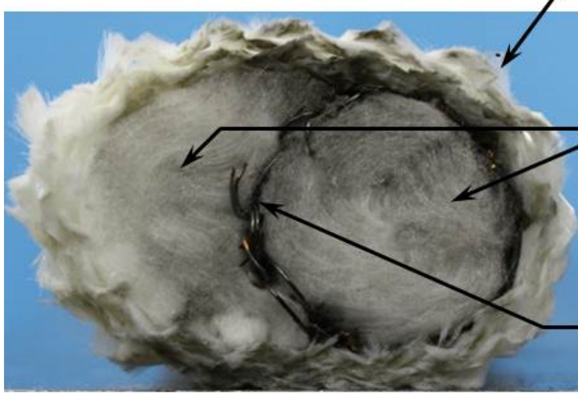
Doors

Control Surfaces

Compliant Thermal Barrier Construction

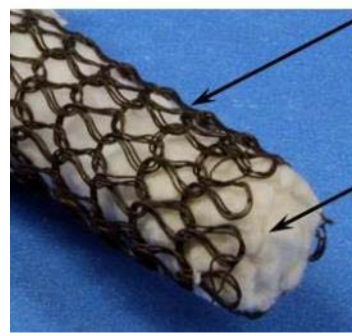


Blanket Thermal Barrier (BTB)



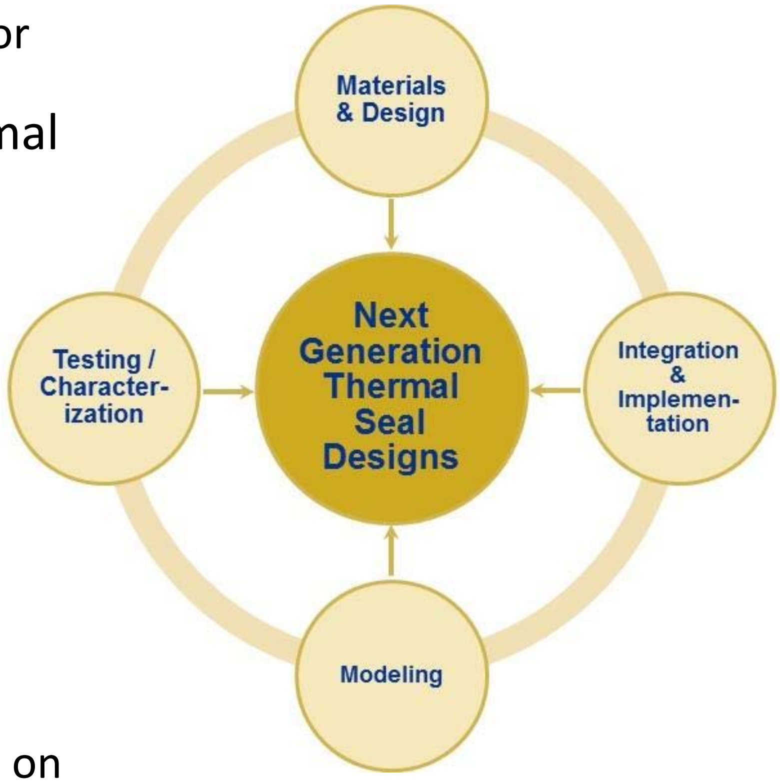
Hybrid Thermal Barrier (HTB)

- Outer sheath
  - 1+ layers of aluminosilicate woven fabric (e.g., Nextel^{TM})
  - Coatings: RTV, emissivity, etc.
- Core
  - Aluminosilicate blanket (e.g., Saffil)
  - Metallic spring tube
- Other
  - Stitching to control shape/size and keep insulation intact
  - End treatments/closeouts



Objectives

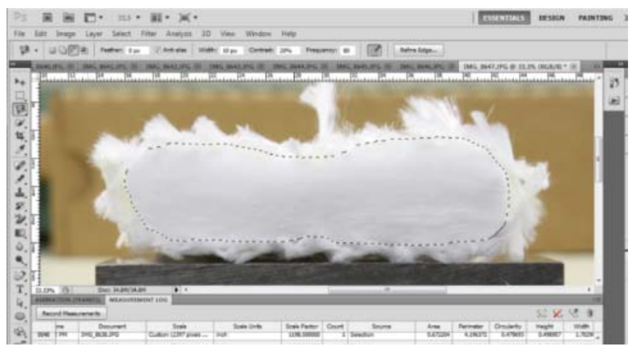
- Thermal barriers are both simple and complex…
  - Simple in basic design and operation
  - Complex in fabrication and mechanistic behavior
- Vehicle designers need help in integrating thermal barriers
  - How big?
  - What configuration? Coatings?
  - How much insulation?
  - How to integrate?
- Objectives: Utilize testing and modeling to
  - Improve understanding of thermal barriers
  - Facilitate improved and more efficient design practices
  - Determine effect insulation core characteristics on thermal barrier performance



Measurement of Core Density

- 3 different methods to measure core density
  - Laser dimensional measurement
  - Photographic dimensional measurement
  - Volume measurement (Archimedes’ Principle)
- Each method has pro’s and con’s
  - Laser and photographic methods quick, but rely on assumptions about core shape
  - Archimedes’ is most accurate, but more complicated
- Core density as a function of compression (“effective density”) required for current study

Laser

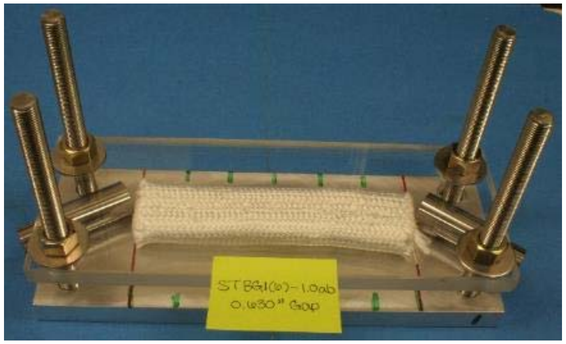


Photographic

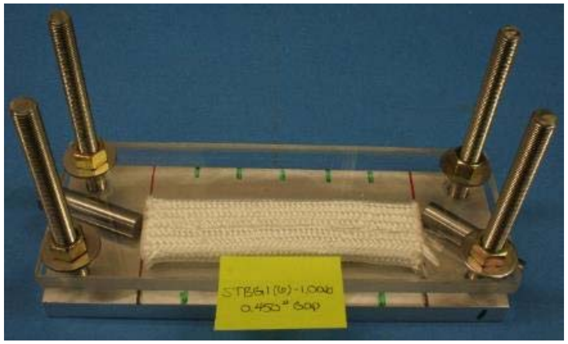
Archimedes

MEASUREMENT OF "EFFECTIVE DENSITY"

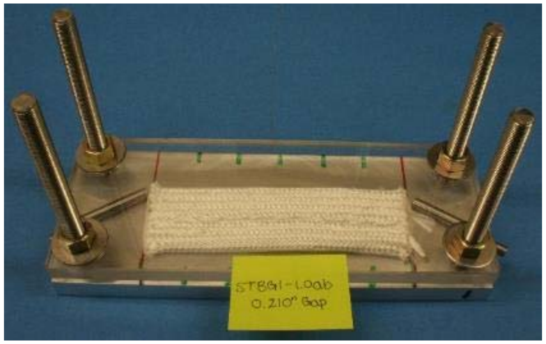
- "Effective density" accounts for volume change and densification of core with respect to compression
- Method
  - Compressed thermal barrier using thick Plexiglass plate to prescribed compression amount set by gage pins
  - Used 2D laser to measure width and thickness in 5 locations along length
  - Estimated core volume from "cross-sectional" and length measurements
- "Effective density" calculated for 3 compression levels (gaps)



Large Gap

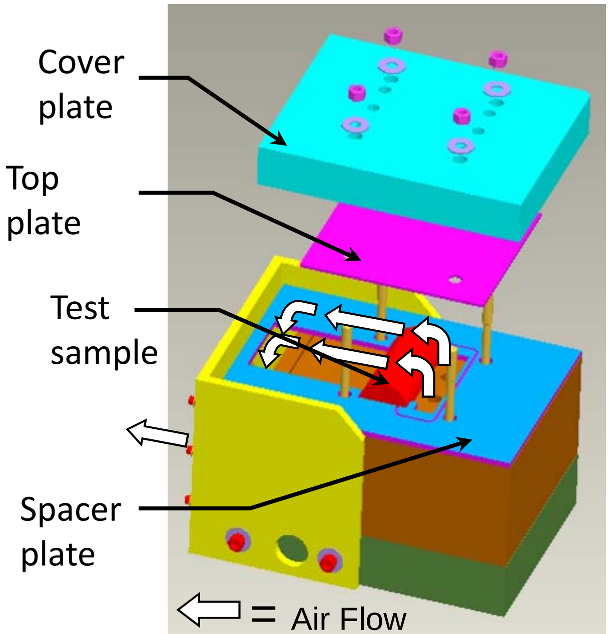


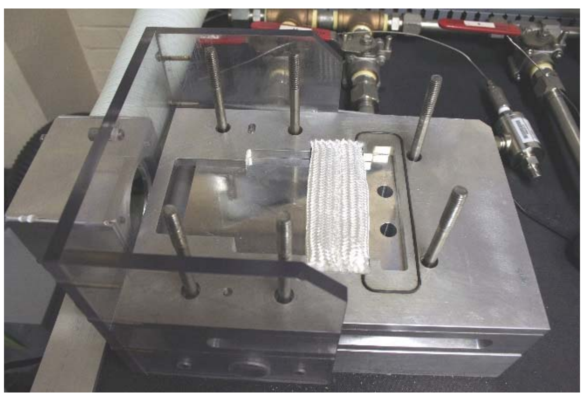
Medium Gap



Small Gap

Measurement of Leakage

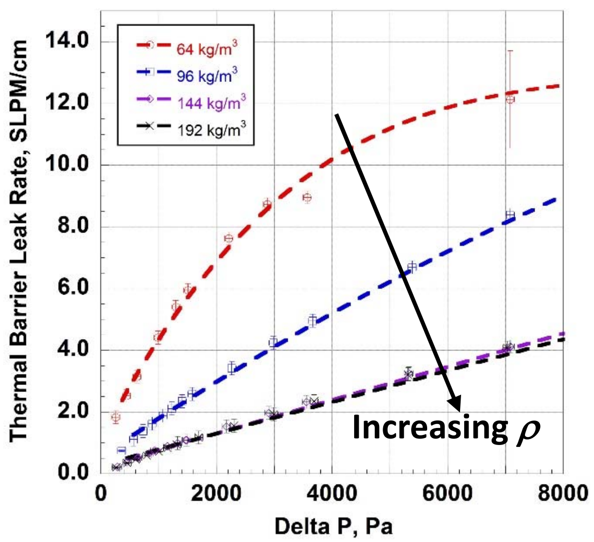




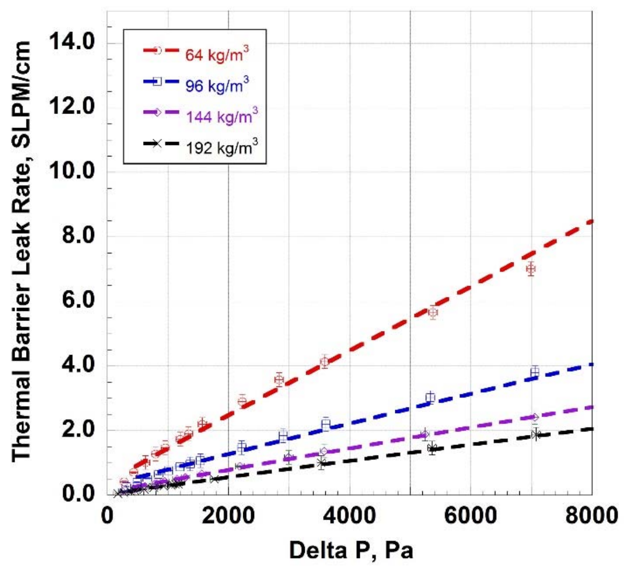
- Thermal barrier tested in Linear Flow Fixture #2 (LFF#2)
- 2 CTB types
  - Blanket (BTB): 64, 96, 144, 192 kg/m^3 nominal core density
  - Hybrid (HTB): 64, 144 kg/m^3 nominal core density
- Test parameters
  - Ambient temperature
  - 3 different gap/compression levels
  - Evaluated between smooth metal plates
  - Delta P: 0 – 7000 Pa
  - Flow measured as function of ΔP across seal

Leakage Results: Blanket Thermal Barrier

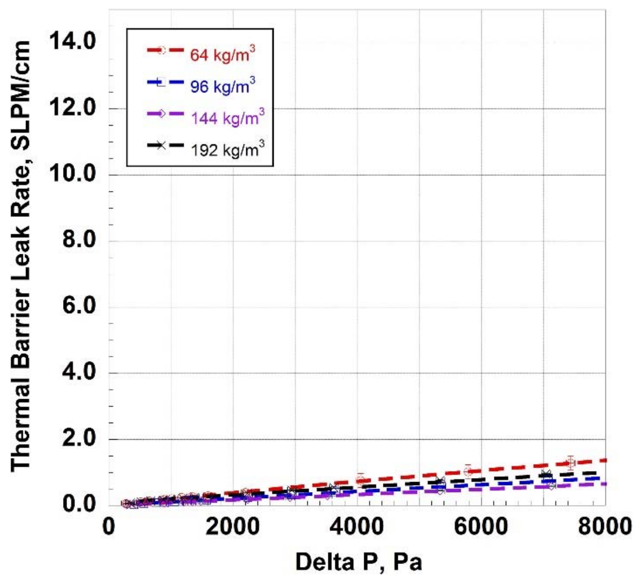
Large Gap



Medium Gap

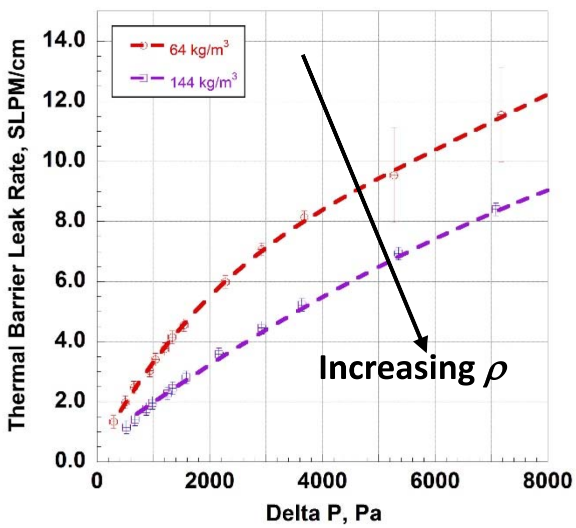


Small Gap

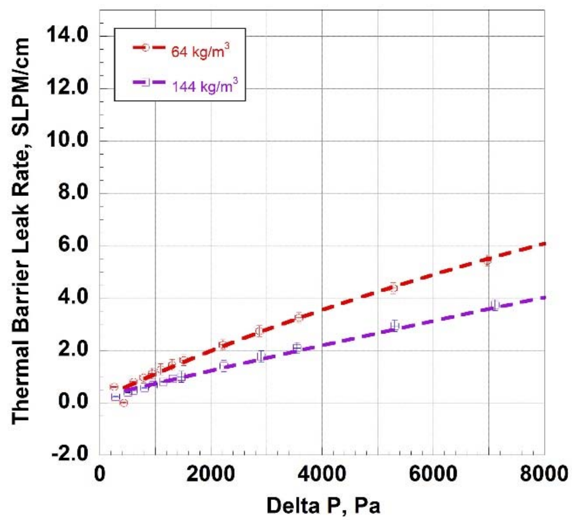


LEAKAGE RESULTS: HYBRID THERMAL BARRIER

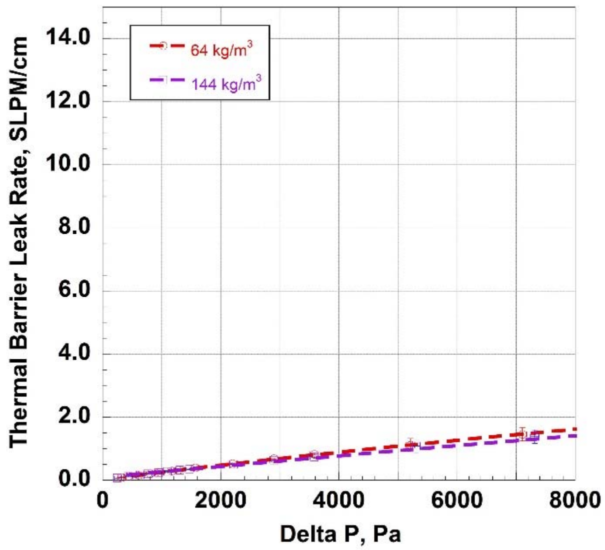
Large Gap



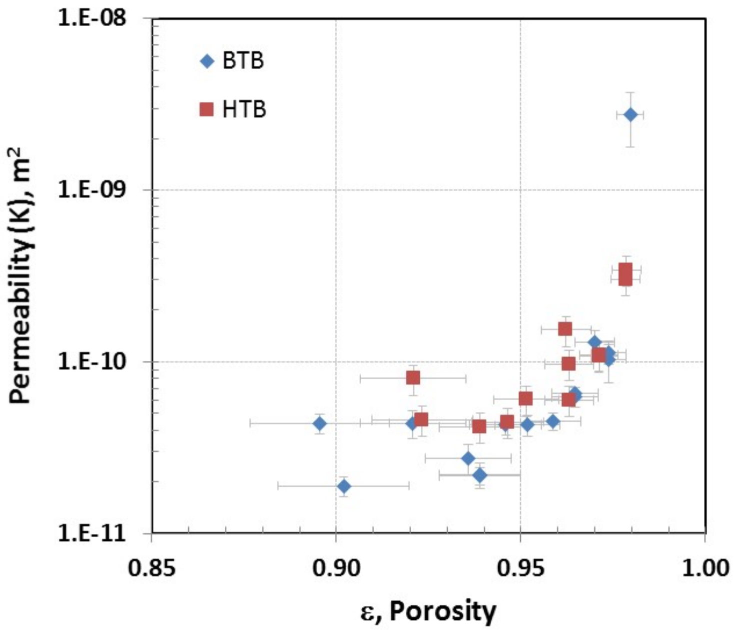
Medium Gap



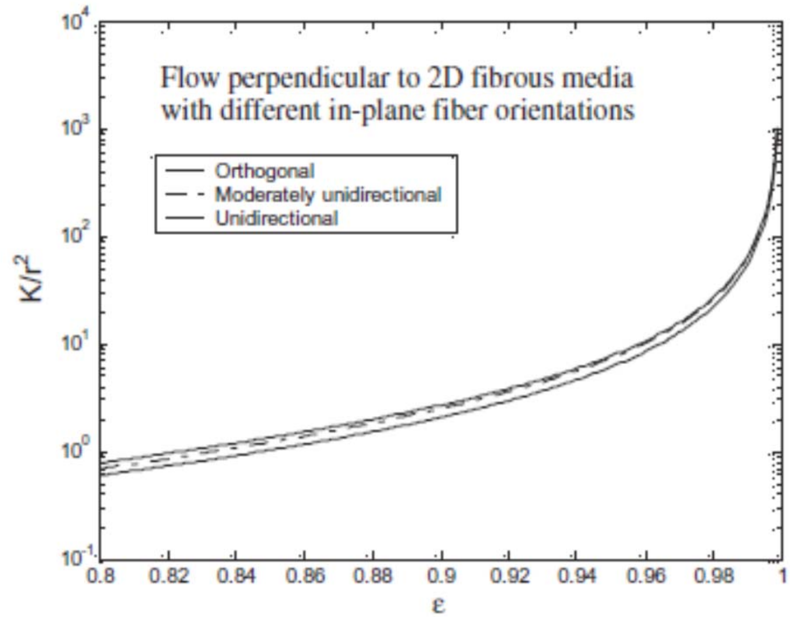
Small Gap



EFFECT OF CORE DENSITY ON PERMEABILITY



(DeMange, unpublished)



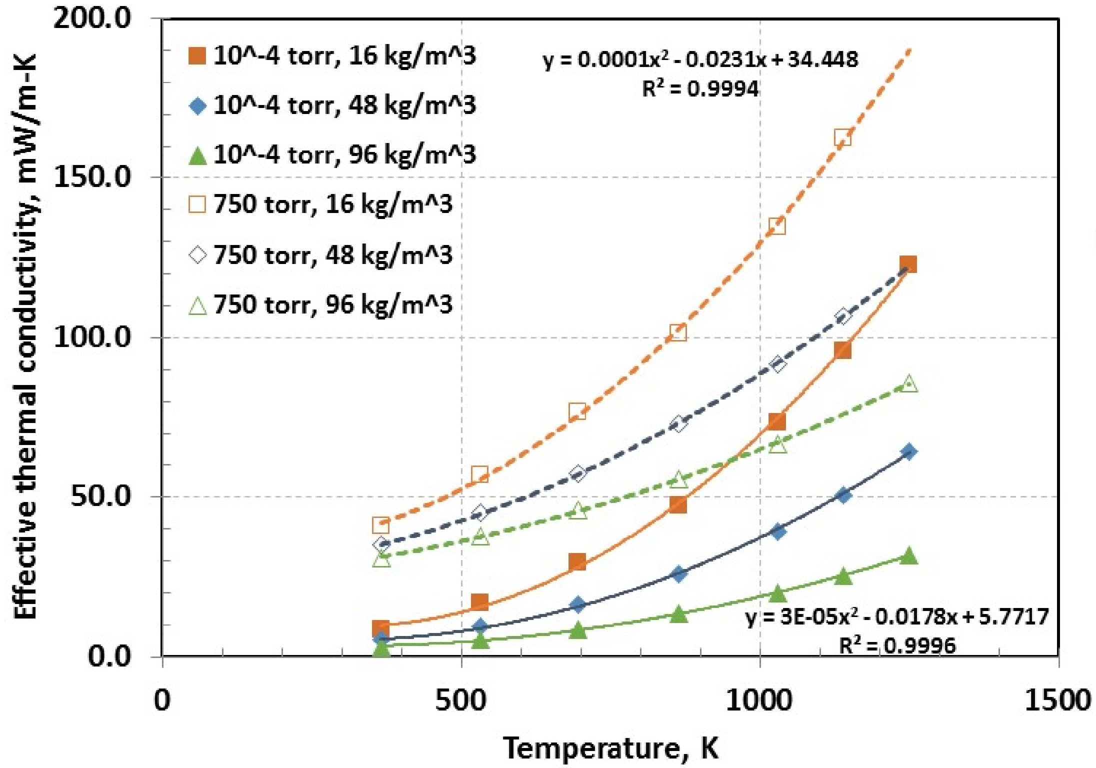
(Shuo *et al.*, 2011)

$$-\nabla P = \frac{\mu}{K}\vec{u} + \rho C|\vec{u}|\vec{u}$$

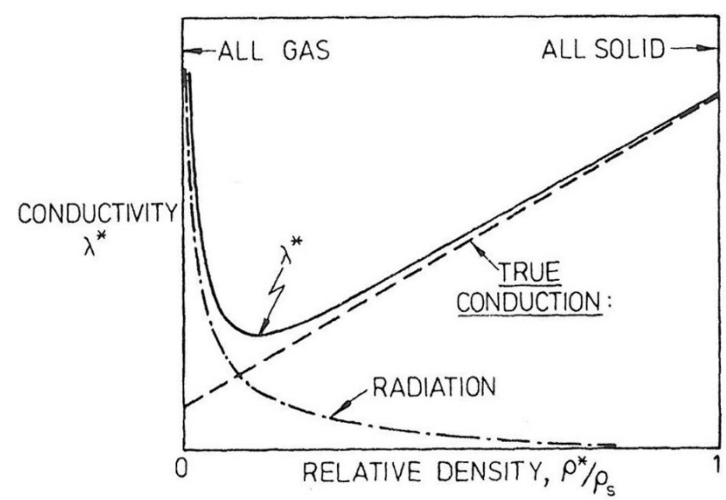
(Stanek & Szekely, 1974)

$$\frac{(P_1^2 - P_0^2)A}{2\dot{m}\mu RTL} = \frac{1}{K} + C\,\frac{\dot{m}}{A\mu}$$

Effect of Core Density on Effective Thermal Conductivity



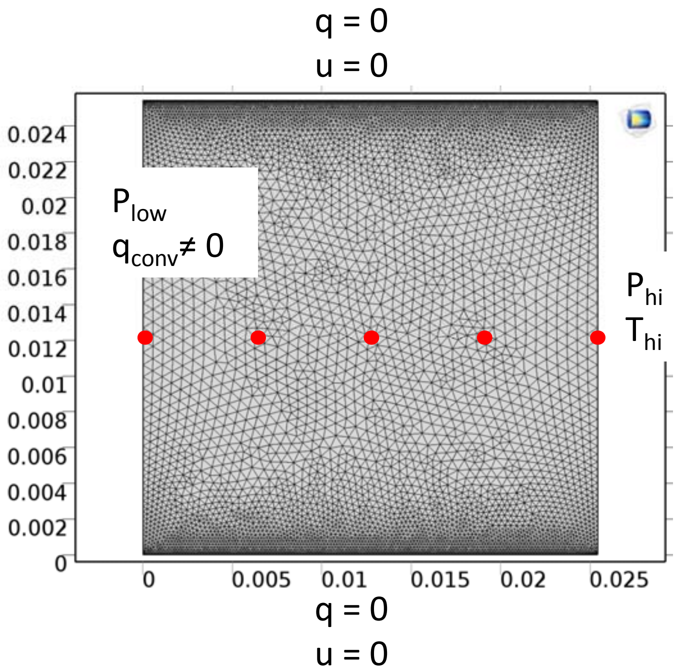
(Daryabeigi, 1999)



(Gibson & Ashby, 1997)

THERMAL MODELING OF SOFT GOOD THERMAL BARRIERS

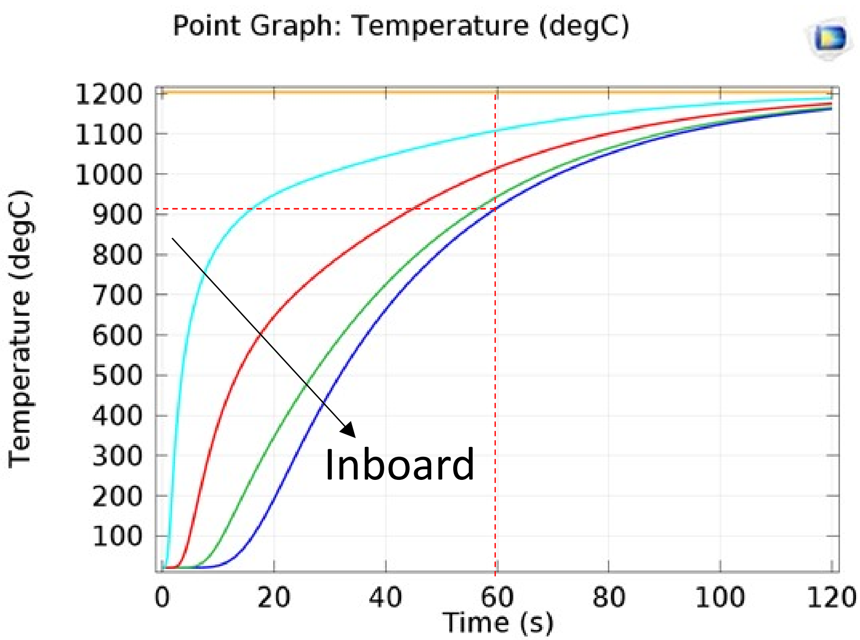
User-controlled mesh
Fluid dynamics – Extra fine
11524 Elements
DOF = 82300 (886 internal DOF)



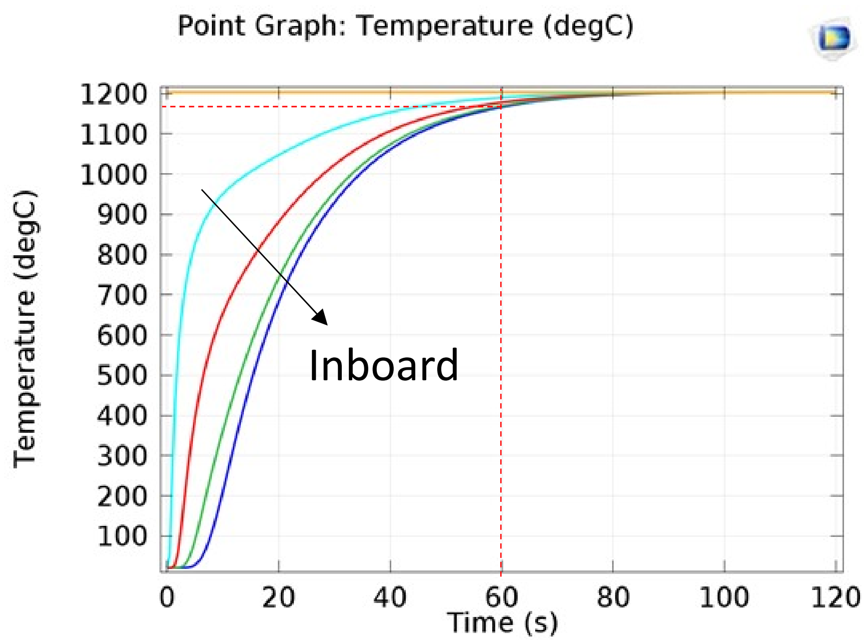
- Modeled using COMSOL 5.0
  - Heat Transfer in Porous Media
  - Free and Porous Media Flow
  - Standard Transient Navier-Stokes Formulation
- Geometry and Boundary conditions
  - Geometry: 2.54 x 2.54 cm square
  - Monitor pts: 5 equally spaced centrally along flow length
  - Outboard
    - P_{hi}: 1500 Pa - 3500 Pa
    - T_{hi}: 1204°C
  - Inboard
    - P_{low}: 100 Pa
    - T_{low}: Outflow (convection-dominated)
  - Top and bottom: Insulative, no slip
- Material properties
  - Density: 60 – 144 kg/m^3
  - Permeability: 0.20 x 10^{-10} – 27 x 10^{-10} m^2
  - Porosity: 90 - 95%
  - Thermal conductivity: High and low
  - Cp = 1000 J/kg-K

EFFECT OF POROSITY

ε = 0.90



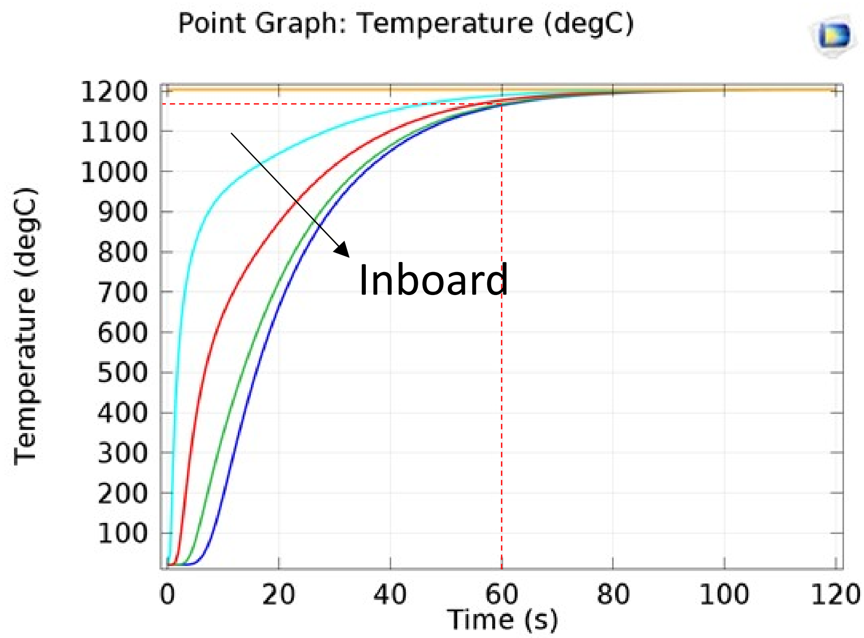
ε = 0.95



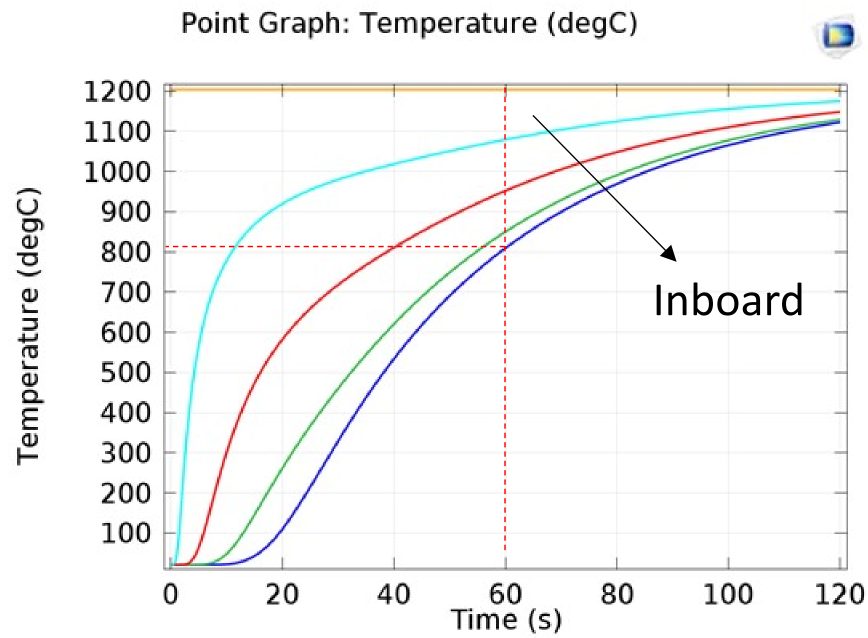
ρ = 120 kg/m^3
K = 3.5E-10 m^2
P_{hi} = 1500 Pa
P_{low} = 100 Pa
T_{hi} = 1204°C
k = (3E-05*T^2-0.0178*T+5.7717)/1000 W/m-K

EFFECT OF INSULATION DENSITY

ρ = 60 kg/m^3



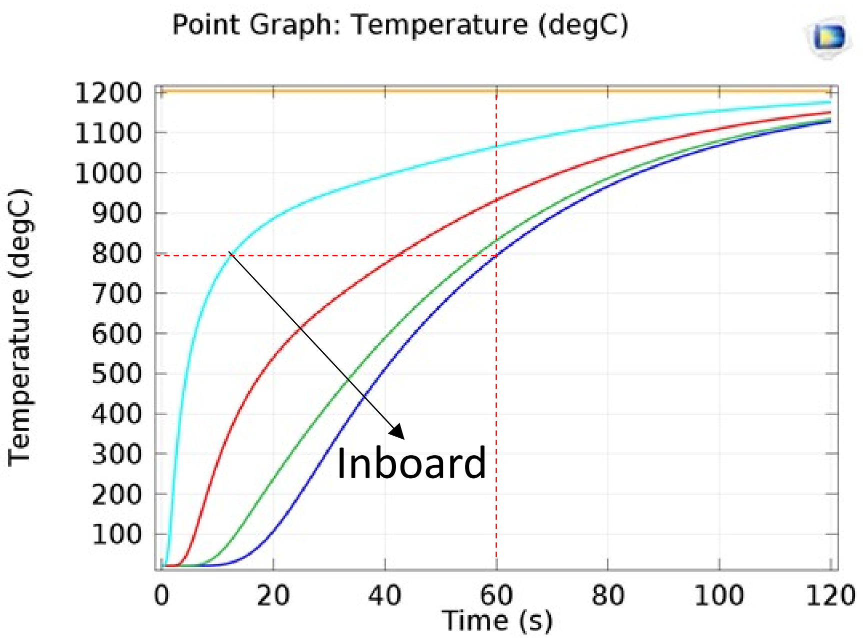
ρ = 144 kg/m^3



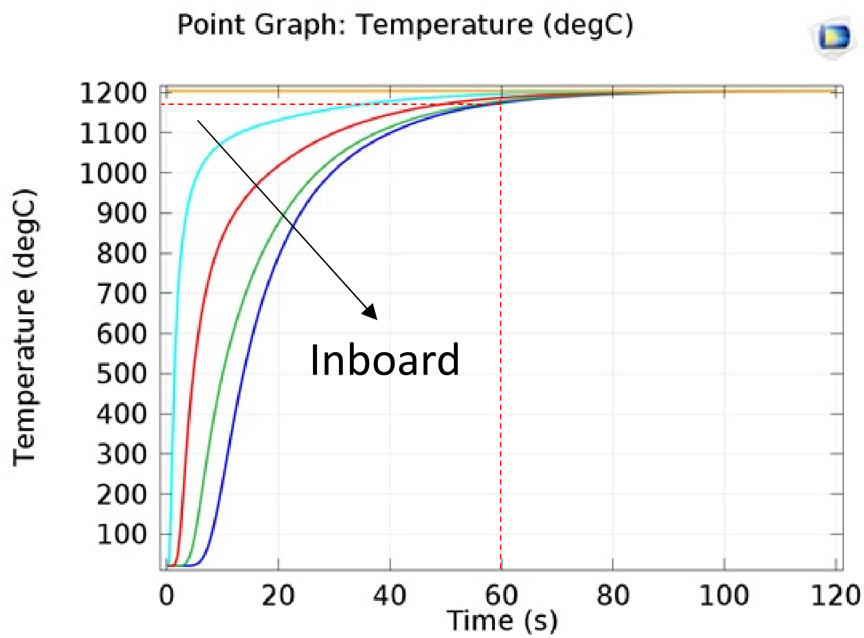
K = 3.5E-10 m^2
P_{hi} = 1500 Pa
P_{low} = 150 Pa
T_{hi} = 1204°C
k = (3E-05*T^2-0.0178*T+5.7717)/1000 W/m-K

EFFECT OF PERMEABILITY

$K = 0.20 \times 10^{-10}\ m^2$



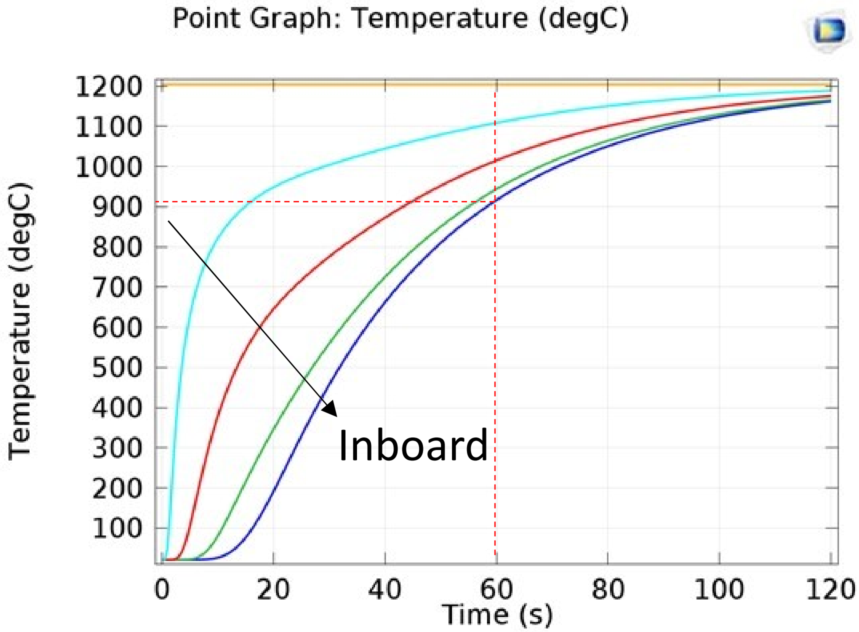
$K = 27 \times 10^{-10}\ m^2$



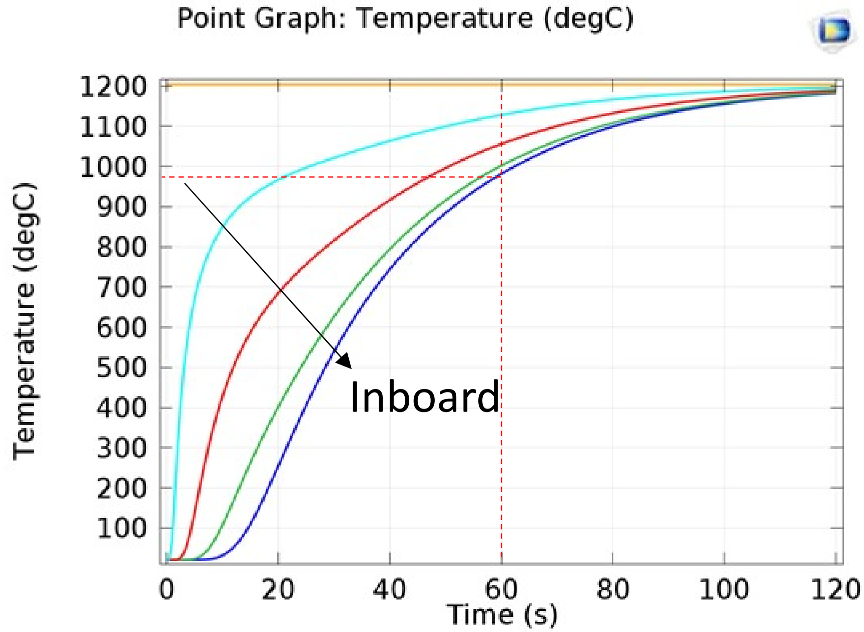
$\rho = 120\ kg/m^3$
$P_{hi} = 1500$ Pa
$P_{low} = 100$ Pa
$T_{hi} = 1204°C$
$k = (3E\text{-}05*T^2 - 0.0178*T + 5.7717)/1000$ W/m-K

Effect of Thermal Conductivity

$k = 3E\text{-}05*T^2 - 1.78E\text{-}2*T + 5.772$ mW/m-K
(lower)



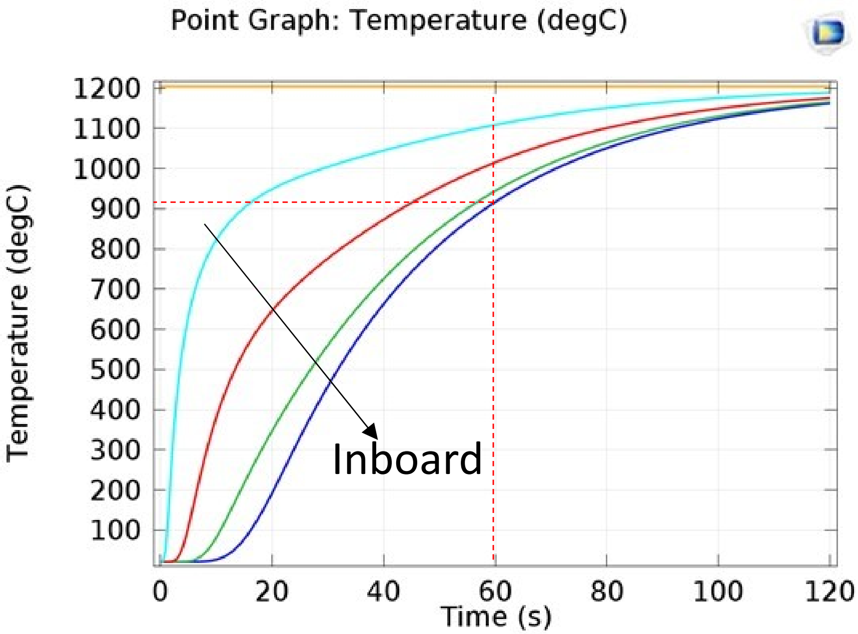
$k = 1E\text{-}4*T^2 - 2.31E\text{-}2*T + 34.448$ mW/m-K
(higher)



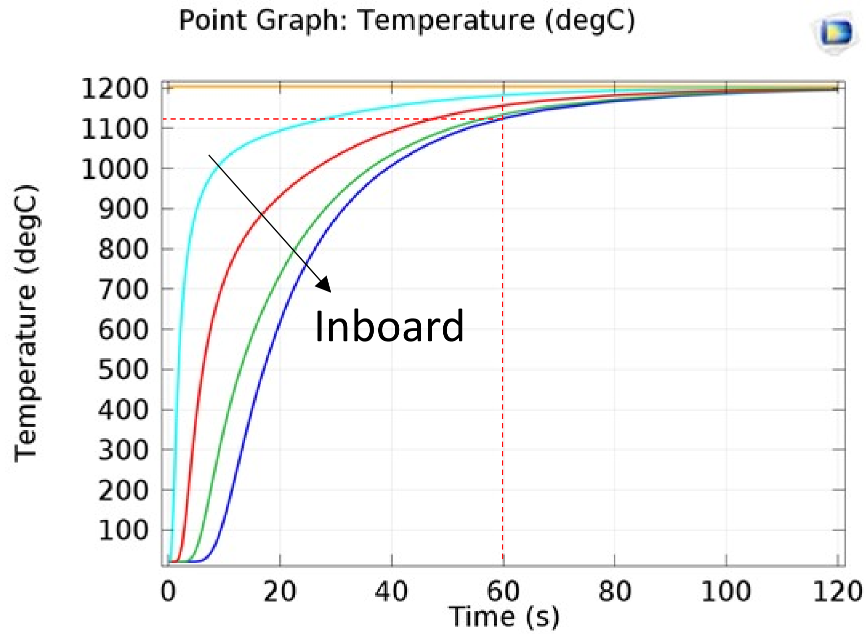
$\rho = 120$ kg/m^3
$K = 3.5E\text{-}10$ m^2
$P_{hi} = 1500$ Pa
$P_{low} = 100$ Pa
$T_{hi} = 1204$°C

EFFECT OF PRESSURE DIFFERENTIAL

P_{hi} = 1500 Pa



P_{hi} = 3500 Pa

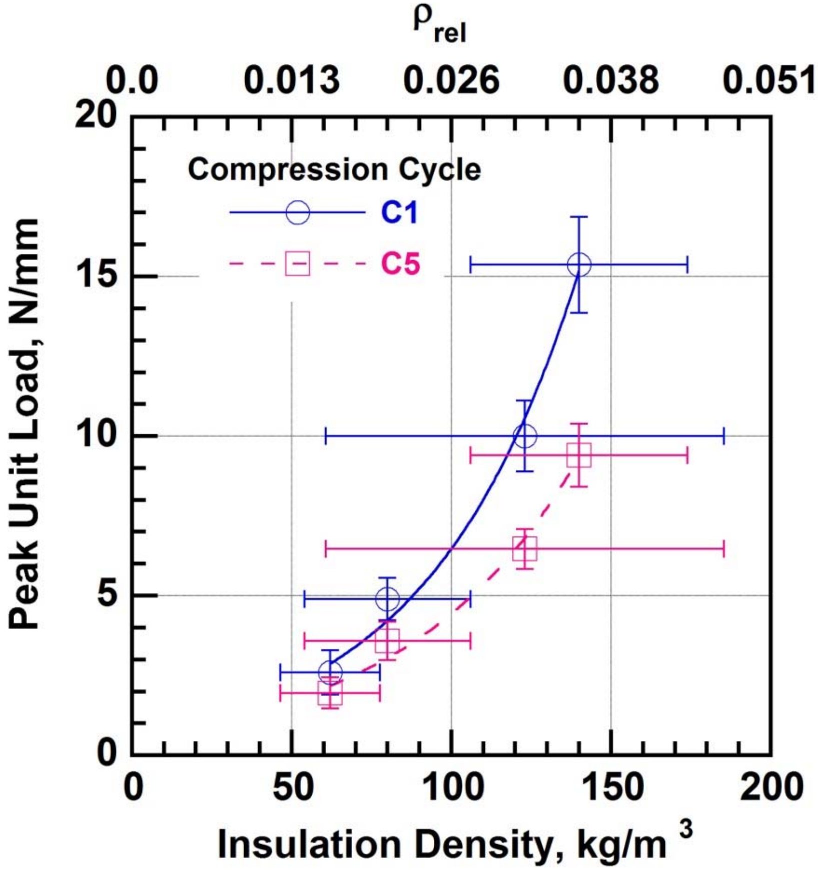


$K = 3.5E\text{-}10\ m^2$
$\rho = 120\ kg/m^3$
P_{low} = 100 Pa
T_{hi} = 1204°C
$k = (3E\text{-}05*T^2\text{-}0.0178*T+5.7717)/1000$ W/m-K

THE TRADEOFF

But…

What may be good thermally, may not be so good structurally.



Summary & Conclusions

- More insulation = better thermal performance
  - Convective heat transfer
    - Flow testing and modeling
    - Lower porosity/higher density, higher compression → reduced permeability, reduced leakage
    - Higher pressure differential → more convective heat transfer
  - Conductive heat transfer
    - Thermal testing and modeling
    - Increasing density → lower k_{eff}
    - But…effect is likely asymptotic, may not improve much after a given core density

- More insulation = higher mechanical loads
  - 60 → 144 kg/m^3, peak loads increase by a factor of 3
  - May be issue if installed adjacent to delicate components (e.g., TPS)

- Vehicle designer/integrator needs to optimize design to account for both thermal and mechanical requirements
  - Integrated thermo-structural model would be beneficial
  - Efforts for both thermal and structural models are ongoing

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APPENDIX

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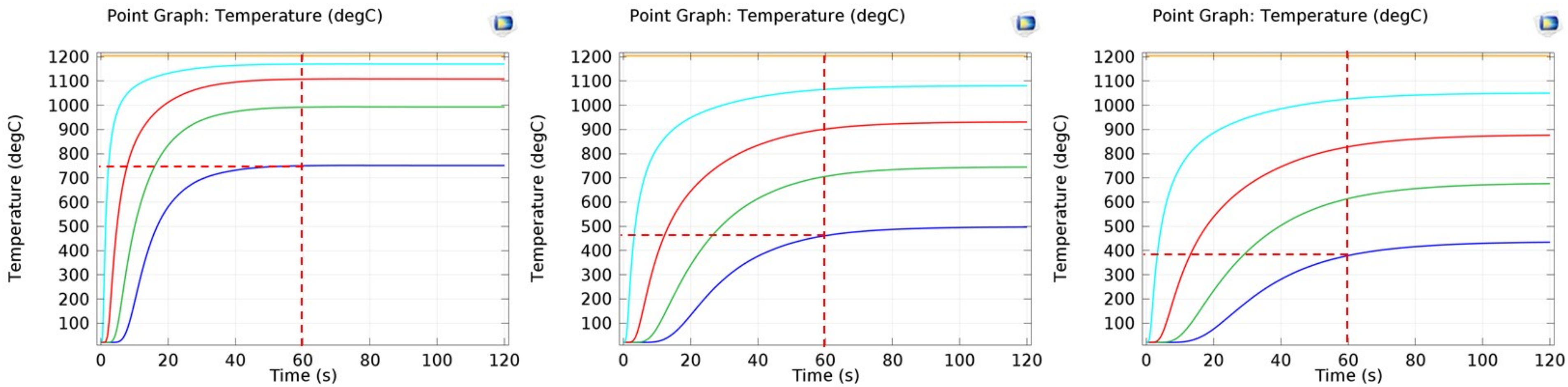
Compliant Thermal Barrier Requirements & Characteristics

- General Requirements
  - Survive in harsh environments (thermally, chemically, tribologically)
  - Mitigate heat transfer
    - Good thermal insulators
    - Minimize convective flow (in combination with inboard environmental barriers)
    - Mitigate radiation heat transfer
  - Exhibit flexibility/conformability
  - Remain resilient
  - Meet load requirements

- Characteristics
  - Made of high temperature ceramic fiber-based materials
  - Utilize high-performance insulation
  - Permeable
  - Compliant
  - Exhibit set/compaction (even at ambient temperatures)
  - Non-linear hysteretic loading behavior

EFFECT OF PERMEABILITY AND REAR BOUNDARY CONDITION

$K = 27 \times 10^{-10}\ m^2$ | $K = 3.5 \times 10^{-10}\ m^2$ | $K = 0.20 \times 10^{-10}\ m^2$



ρ = 120 kg/m^3
P_{hi} = 1500 Pa
P_{low} = 100 Pa
T_{hi} = 1204°C
k = (3E-05*T^2-0.0178*T+5.7717)/1000 W/m-K
Backside convective heat boundary (h = 5 W/m^2-K)